## 2.6 Deep Inelastic Scattering and QCD

Neutrino scattering plays a crucial role in extraction of fundamental parton distribution functions (PDFs). These PDFs describe parton constituents of protons and other hadrons, and (in the $\overline{MS}$ convention) are precisely defined in terms of operator matrix elements. The necessity of neutrino measurements is obvious, because only neutrinos can resolve the flavor of the nucleon's constituents: $\nu$ interacts with $d$, $s$, $\overline{u}$ and $\overline{c}$ while the $\overline{\nu}$ interacts with $u$, $c$, $\overline{d}$ and $\overline{s}$. The weak current's unique ability to "taste" only particular quark flavors significantly enhances the study of parton distribution functions. MINER$\nu$A's high-statistics measurement of the nucleon's partonic structure, using neutrinos, will complement ongoing studies with electromagnetic probes at other laboratories.

Large samples, and dedicated effort to minimizing beam-related systematics will allow MINER$\nu$A to independently isolate all the structure functions $F_1^{\nu N}(x,Q^2)$, $F_1^{\bar{\nu}N}(x,Q^2)$, $F_2^{\nu N}(x,Q^2)$, $F_2^{\bar{\nu}N}(x,Q^2)$, $xF_3^{\nu N}(x,Q^2)$ and $xF_3^{\bar{\nu}N}(x,Q^2)$ for the first time. By taking differences and sums of these structure functions, specific parton distribution functions in a given $(x,Q^2)$ bin can in turn be determined. With the manageable systematic uncertainties expected, MINER$\nu$A will dramatically improve the isolation of individual PDFs by measuring the full set of $\nu$ and $\bar{\nu}$ structure functions.

Extracting this full set of structure functions will rely on the $y$-variation of the structure function coefficients in the expression for the cross-section. In the helicity representation, for example:

$$\begin{aligned}\frac{d^2\sigma^\nu}{dxdQ^2} &= \frac{G_F^2}{2\pi x}\Big[\frac{1}{2}\left(F_2^\nu(x,Q^2)+xF_3^\nu(x,Q^2)\right)+ \\ &\quad \frac{(1-y)^2}{2}\left(F_2^\nu(x,Q^2)-xF_3^\nu(x,Q^2)\right)- \\ &\quad 2y^2F_L^\nu x,Q^2)\Big]. \qquad (1)\end{aligned}$$

By analyzing the data as a function of $(1-y)^2$ in a given $(x,Q^2)$ bin, all six structure functions can be extracted.[1]

The MINER$\nu$A physics program includes systematic measurements of the neutrino cross section and structure function from a variety of nuclear targets. This will be important both to connect with previous measurements which will overlap the MINER$\nu$A result on the high $Q^2$ end and to allow, for the first time, a precision determination of nuclear effects in neutrino scattering.

### 2.6.1 Structure Functions

The structure function $F_2$ has been precisely measured over a large range of $Q^2$ using charged-lepton probes. Figure 1 illustrates the kinematic coverage for measurements of $F_2$ using charged-lepton and neutrino probes. Neutrino measurements have been limited so far to moderate $Q^2$'s. MINER$\nu$A will provide complimentary information from neutrinos in the high-$x$ low-$Q^2$ regime which overlaps precise measurements using charged-lepton probes.

While the structure function $F_2$ is precisely measured with charged-lepton probes, the parity-violating structure function $xF_3$ can best be determined using a weak-interaction probe. Neutrino measurement have been limited to moderate $x$ and $Q^2$. As Figure 2 illustrates, MINER$\nu$A will provide new kinematic coverage for the structure function $xF_3$.

[1] Note that for this type of parton distribution function study, anti-neutrino running will be essential.

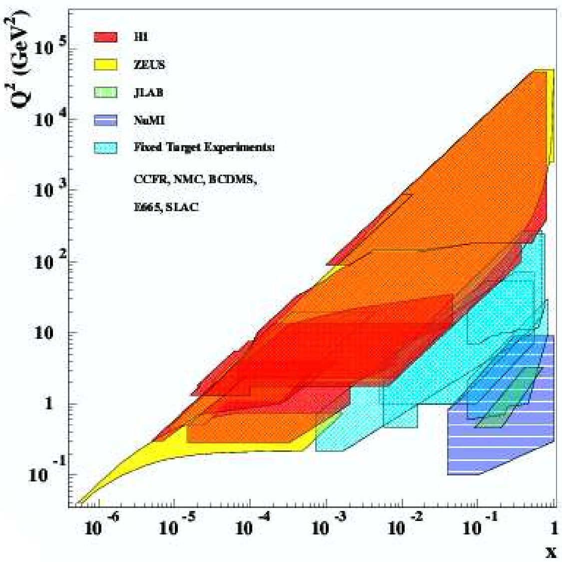


Figure 1: Kinematic coverage of structure function measurements.

## 3 Physics Driven Requirement Structure Function Measurement

There are several components of the MINER$\nu$A detector design that impact DIS physics. In a deeply inelastic event, the probing particle breaks apart the nucleus and a hadronic shower is present in the final state. The detector must have sufficient mass to contain the shower and measure the energy at the hadronic vertex. In MINER$\nu$A the outer detector (OD) serves the function of stopping hadrons and measuring their energy. The design of the OD was optimized to provide adequate hadronic shower energy resolution and good hadron containment.

The measurement of the neutrino differential cross section and structure functions relies on accurate determination of the event kinematic variables. Figure 3 shows the effect of hadron energy resolution on the measured kinematic variable distributions, $x$, $y$, and $Q^2$, for the nominal resolution of $22\%/\sqrt{E_H}$. The hadronic energy resolution has a large impact on the measured $y$ distribution. Figure 4 shows how the smearing changes as the hadron energy resolution is varied from $11\%/\sqrt{E}$ (half the nominal value) up to $44\%/\sqrt{E}$ (twice nominal). Clearly a resolution of twice nominal significantly degrades the measured $y$ distribution, which decreases significantly the ability of MINER$\nu$A to precisely measure the $y$ dependence of the differential cross section and, consequently, extract the complete set of structure functions.

To fully determine the kinematics of a charged-current neutrino scattering event, the momentum of the outgoing muon track must be measured. This adds a requirement that the OD be thick enough to identify tracks exiting the detector and to track them into the minos near detector where their momentum is measured. The MINER$\nu$A design, which uses the minos near detector as a muon spectrometer, has adequate acceptance and momentum resolution for muons. Figure 5 shows the effect of muon momentum resolution on the measured kinematic variable distributions for the nominal muon momentum resolution of 12% for the minos near detector. Figure 6 shows how the smearing changes as the muon momentum resolution is varied from 6% (half the nominal value) up to 24% twice nominal. Clearly

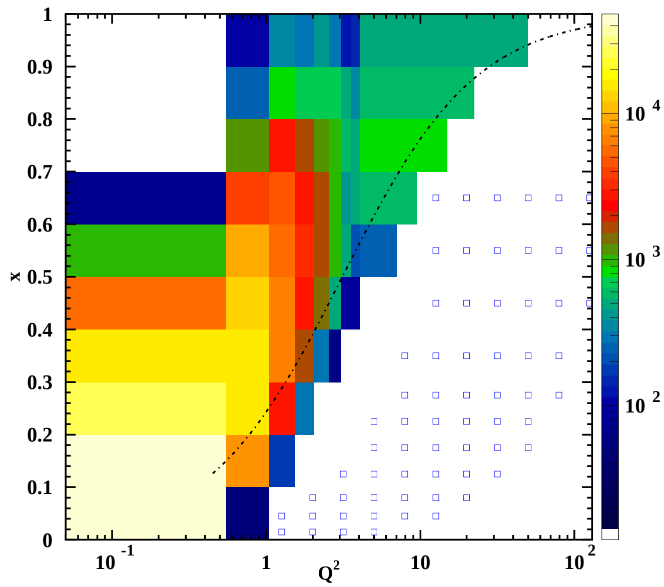


Figure 2: Available $xF_3$ data (open symbols) and the anticipated (resonant region) MINER$\nu$A data (colored distributions) in $x_{Bj}$ vs. $Q^2$. The curve indicates the commonly-accepted $W^2$ = 4 GeV$^2$ boundary between the resonant and deep-inelastic regimes. The color key to the right shows the corresponding, expected MINER$\nu$A statistics.

the resolution of 24% has significantly degraded the measured $x$ and $Q^2$ distributions, which decreases significantly the ability of MINER$\nu$A to measure structure functions.

Accurate measurement of the structure functions also requires precise control of systematic uncertainties. The largest systematic uncertainties arise from knowledge of the experiement's absolute energy scale. This affects measurement of the kinematic variables and limits how well the $Q^2$ dependence of the structure functions can be determined. Figure 7 shows the effect of two values of energy scale uncertainty on measurement of the structure function $F_2$.

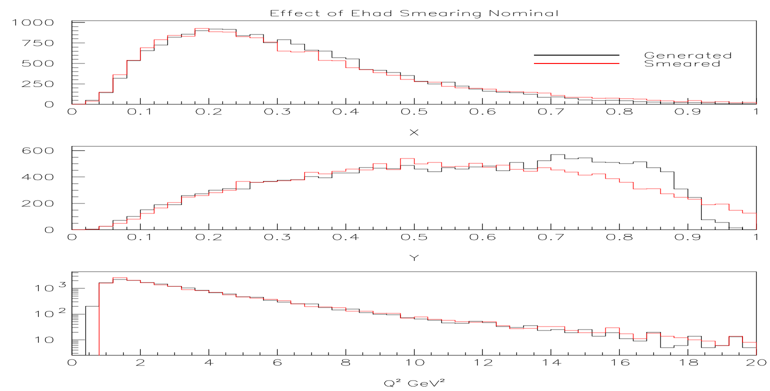


Figure 3: Effect of hadron energy resolution on the measured kinematic variable distributions ($x$, $y$, and $Q^2$) for the nominal resolution of 22%/$\sqrt{E_H}$.

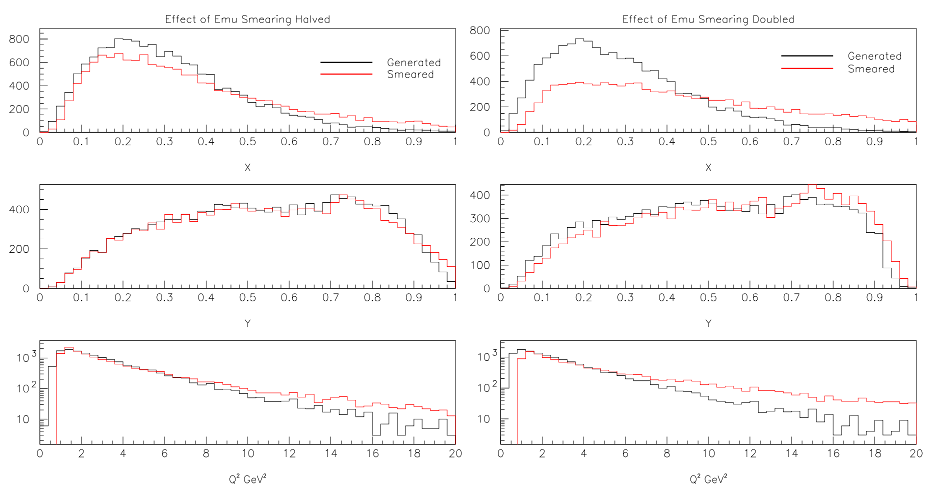


Figure 4: Effect of hadron energy resolution on the measured kinematic variable distributions ($x$, $y$, and $Q^2$) for the resolution of 11%/$\sqrt{E}$ (left) and 44%/$\sqrt{E}$ (right).

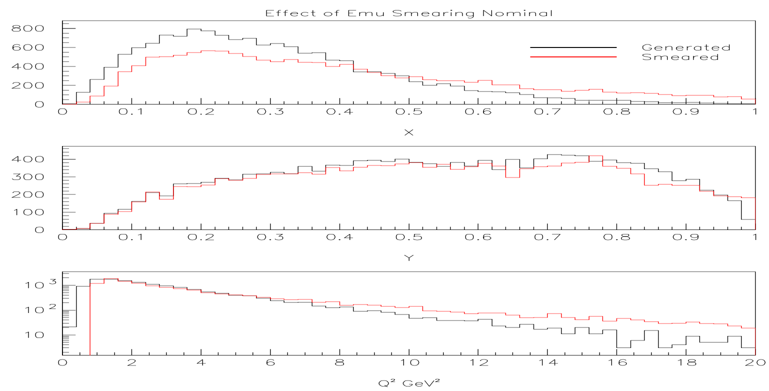


Figure 5: Effect of muon momentum resolution on the measured kinematic variable distributions ($x$, $y$, and $Q^2$) for the nominal muon momentum resolution of 12% for the minos near detector.

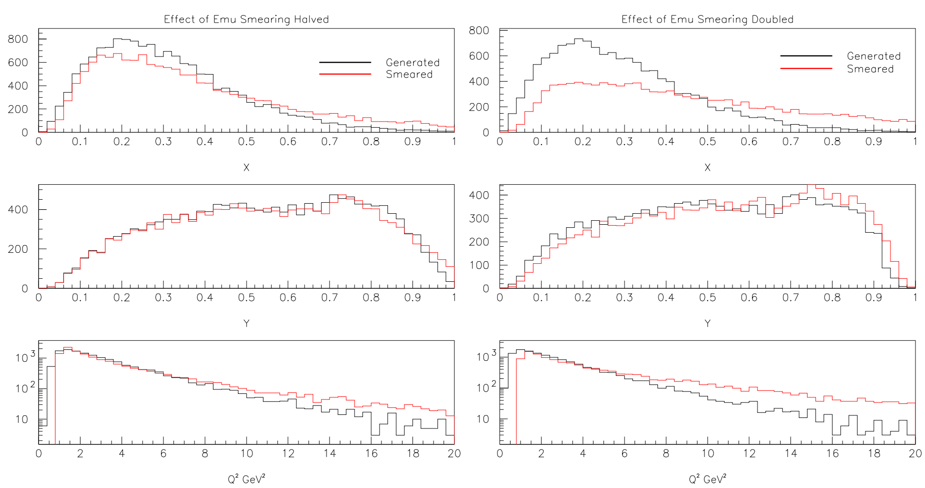


Figure 6: Effect of muon momentum resolution on the measured kinematic variable distributions ($x$, $y$, and $Q^2$) for the muon momentum resolution of 6% (left) and 24% (right).

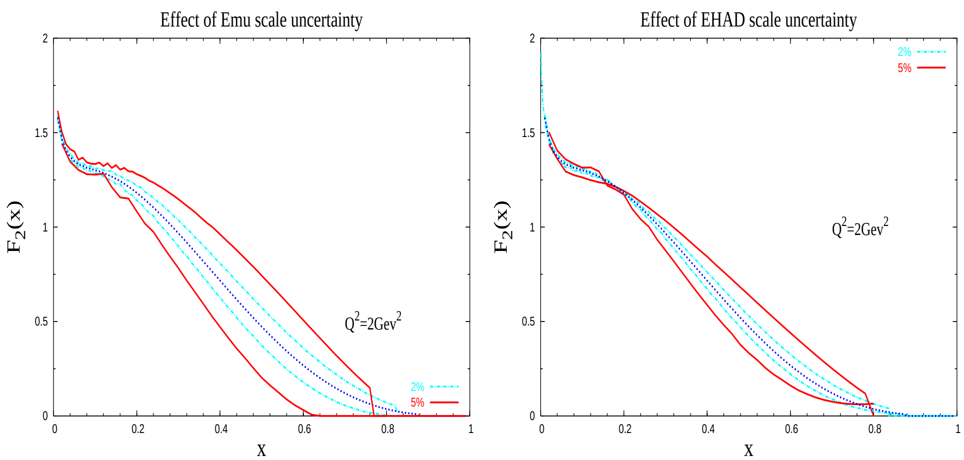


Figure 7: Effect of energy scale uncertainties on $x$-dependence of $F_2$ at $Q^2$=2GeV$^2$. Uncertainty due to muon energy scale is shown on the left for 2%(blue) and 5% (red) scale uncertainties. The same curves for hadron energy scale are shown on the right.